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IN SITU BURNING OF OIL SPILLS: SMOKE PRODUCTION AND PLUME BEHAVIOR

David D. Evans
Large Fire Research Group
Building and Fire Research Laboratory
National Institute of Standards and Technology
Gaithersburg, Maryland 20899

SUMMARY

In 1985, the National Institute of Standards and Technology (NIST) began a study of in situ burning of crude oil to provide information to support decisions about the use of this technology for oil spill response. Measured smoke production from burning of crude oils in the laboratory, in mesoscale experiments, and in an offshore experiment are presented. Calculations of smoke plume dispersion for an oil spill burn in the vicinity of Cook Inlet, Alaska show that beyond 5 km downwind of the burn, smoke particulate concentrations near the ground averaged over 1 hour do not exceed 150 $\mu g/m^3$.

INTRODUCTION

In situ burning of spilled oil has distinct advantages over other countermeasures. It offers the potential to convert rapidly large quantities of oil into its primary combustion products, carbon dioxide and water, with a small percentage of smoke particulate and other unburned and residue byproducts. Burning of spilled oil from the water surface reduces the chances of shoreline contamination and damage to biota by removing the oil from the water surface before it spreads. In situ burning requires minimal equipment and less labor than other techniques. It can be applied in areas where many other methods cannot due to lack of response infrastructure and/or lack of alternatives. Oil spills amongst ice and on ice are examples of situations where practical alternatives to burning are very limited. Because the oil is mainly converted to airborne products of combustion by burning, the need for physical collection, storage, and transport of recovered fluids is reduced to the few percent of the original spill volume that remains as residue after burning.

Burning oil spills produces a visible smoke plume containing smoke particulate and other products of combustion which may persist over many kilometers downwind from the burn. This fact gives rise to public health concerns, related to the chemical content of the smoke plume and the downwind deposition of particulate, which need to be answered. The program of research in oil spill burning began at NIST in 1985 addresses this need for information through measurements and calculations.

BACKGROUND

As a result of 1983 experiments in which 50 to 95 percent of all the oils tested were removed from the water surface by burning in the Oil and Hazardous Materials Simulated Environmental Test Tank (OHMSETT) facility in Leonardo, New Jersey [1], studies were initiated at the NIST under funding from the Minerals Management Service (MMS). The NIST research program was designed to study how burning large oil spills would affect air quality by quantifying the products of combustion and developing methods to predict the downwind airborne smoke particulate concentrations. Measurements were performed at three scales. Initially, laboratory experiments of 0.4 m to 1.2 m diameter pool fires were conducted to measure burning rates and smoke product in a controlled environment [2]. Subsequent mesoscale burn experiments up to 15 m square were conducted outdoors to examine scaling of laboratory results to a size approaching that expected to be used in oil spill mitigation. New instrumentation techniques were developed to perform measurements of smoke production in a free smoke plume [3]. These measurement methods were employed in the large scale experiments conducted recently in at sea burns off the coast of Newfoundland, Canada [4].

Concurrent with the development of measurements techniques for smoke plumes, a Large Eddy Simulation (LES) model for the calculation of smoke plume trajectory and predicting the "footprint" of soot particle deposition downwind of a burn was developed. LES is a steady-state three-dimensional calculation of smoke plume trajectory and smoke particulate deposition based on a mixed finite difference and Lagrangian particle tracking method [3].

SMOKE YIELD

The smoke production from a fire may be expressed in terms of a smoke yield Y_S which is defined as the mass of smoke particulate m_P produced from burning a fuel mass m_F, as:

$$Y_S = \frac{m_P}{m_F} \tag{1}$$

The mass of carbon in the fuel that is consumed by burning is equal to the mass of carbon in the smoke plume.

$$m_{C,Smoke} = m_{C,Fuel} \tag{2}$$

Three assumptions are made in the analysis. The first is that the smoke particulate is predominately carbon. Previous laboratory measurements [5] have shown that the organic carbon fraction of smoke from crude oil pool fires is not greater than 10 percent before

there is any boiling in the supporting water sublayer. The remainder of the smoke contains greater than 90 percent elemental carbon. Thus the total carbon content which includes the elemental carbon and the carbon contained in the organic fraction is well over 90 percent of the content of the smoke. Based on this evidence, for the purpose of the smoke yield analysis, the smoke particulate is considered to be pure carbon. The second assumption is that samples are collected over a suitable time period to average out natural fluctuations in the fire and plume. In the mesoscale tests and laboratory tests, samples are drawn over a period of 600 seconds to over 1000 seconds. This is deemed sufficient to represent the average burning conditions for the fires. The third assumption is that no preferential separation of smoke particulate and combustion gases occur in the smoke plume up to the point where the sample is taken. In all field measurements, and unconfined laboratory burns, the smoke yield measurement is made close to the source where the smoke and gaseous combustion products move in a well formed smoke plume. Combining eqs (1) and (2) and taking into account the three assumptions above yields:

$$Y_S = \frac{m_P}{m_{C,Smoke}} \quad \frac{m_{C,Fuel}}{m_F} \tag{3}$$

To evaluate the above ratio, a known volume of smoke is drawn though a filter and the gaseous portion collected in a sample bag. The mass of carbon in the smoke ($m_{C,Smoke}$) is equal to the mass of carbon in the smoke particulate, assumed equal to the mass of particulate (m_p) collected on the filter, plus the mass of carbon in the CO_2 and CO in the gaseous portion of the smoke sample. The second fraction on the right-hand-side of eq (3), the mass fraction of carbon in the fuel, is determined from an elemental analysis of the fuel. For example, the ratio,

$m_{C,Fuel}/m_F$ for Louisiana crude oil, is 0.858, which is typical for crude oils.

Controlled laboratory experiments provided the opportunity to evaluate if the smoke yield measurements are constant over the entire cross section of the smoke plume. Following the assumption that both the gases and the particulate travel together near the fire mixing with the entrained air as the smoke moves away from the source, the smoke yield should be equal when measured at the center of the plume and at its edge. In mesoscale tests, due to variations in the wind, natural fluctuations in the fire, and difficulties in positioning smoke measurement instruments which are suspended below a tethered blimp, the smoke samples are drawn from a variety of positions within the plume over the long sampling time. Therefore it is important to assure the accuracy of these measurements, and that position is not a sensitive factor in the smoke yield measurement.

Table 1. Smoke yield from laboratory burn

Location	Smoke Yield (%)
Plume centerline	10.90
1 m radial from plume centerline	10.90
1 m radial from plume centerline	10.68
2 m radial from plume centerline	11.07
2 m radial from plume centerline	10.76

In the laboratory burn of a 1.2 m diameter Louisiana crude oil pool fire [6], smoke yield measurements were made at three positions: plume centerline, 1 m radius and 2 m radius (near the edge of the visible plume) at a height of 15 m above the burning fuel surface. Table 1 shows the results of the measurements. The smoke yield is seen to be nearly constant across the plume and the measurement method is seen to be repeatable at each measurement station. The average smoke yield for the 1.2 m diameter Louisiana crude oil fire is 10.9 percent.

Smoke yields from the larger mesoscale burns (6.88 m and 17.2 m effective diameter) are given in table 2. It appears that smoke yield in the 1.2 m diameter laboratory fires (10.9%) is a good indicator of smoke yield from the 17.2 m diameter fires (10.5% average of five tests [6]). This result based on measurement of a single crude oil type should be regarded as preliminary. Also, the single 6.88 m fire measured produced a larger smoke yield than the 17.2 m burn which has four times the burning surface area [6]. This result is interesting as it suggests that either there is peak in the smoke production rate, or that there is a characteristic of the 6.88 m diameter fires that has not been taken into account. Both 1.2 m and 17.2 m fires produced significantly less smoke per unit mass of fuel consumed than the 6.88 m burn. In field tests of in situ oil spill burning off the coast of Newfoundland [4], a smoke yield of nominally 15 percent was measured for weathered Alberta Sweet Mixed Blend crude oil.

Table 2. Smoke yield from mesoscale and field burns

Crude Oil	Effective Burn Diameter (m)	Smoke Yield (%)
Louisiana [6]	6.88	14.0 - 15.2
Louisiana [6]	17.2	9.4 - 12.3
Alberta Sweet Mixed Blend	Varied*	14.8 - 15.2

* NOBE field test [4]. Oil burned in the apex of a 150 m long boom towed in a U-configuration, August 12, 1993

Table 3. Smoke Yield from Crude Oils Fires (1.2 m diameter)

Crude Oil	Smoke Yield (%)
Louisiana [6]	10.9
Cook Inlet [7]	9.2
Alaska North Slope [7]	11.6

Table 3 shows the results of laboratory burns of three crude oils in 1.2 m diameter pans. The smoke yield for each was slightly different but nominally 10 percent.

SMOKE PLUME BEHAVIOR

NIST is developing the LES (Large Eddy Simulation) smoke plume trajectory model to address the need for accurate predictions of downwind smoke dispersion from large buoyant sources such as oil spill fires to support the decision process about the application of in situ burning in response to oil spills. This model differs from most of the atmospheric dispersion models in use today because it is a *deterministic* rather than an *empirical* model; that is, the approach taken is to solve the governing equations of motion directly rather than relying on empirical formulae which approximate the extent of the dispersion. These empirical models typically assume the pollutant of interest to be Gaussian distributed in the plane perpendicular to the direction of the prevailing wind. The parameters defining the distribution are estimated from experiments. Unfortunately, the problem of in situ burning of crude oil is inappropriate for these types of models for two reasons: (1) The nature of the "source" is different than what is normally assumed, a smokestack, and (2) the size of the source is well beyond those considered in industrial applications and thus outside of the experimental parameter range.

Because the LES model approaches the dispersion problem from first principles, it is more flexible, and ultimately easier to apply because it reduces the number of empirical parameters demanded of the user. The long range goal of the LES modeling study is to provide high resolution predictions that can account for the actual terrain and atmospheric conditions in the vicinity of the spill. LES version 2.0 was used to predict smoke plume trajectory from oil spill burns in Alaska [7]. This version of the model is limited to predictions of downwind smoke concentration for uniform winds and flat terrain. Details of the model derivation are given in reference [7].

Application of the model is demonstrated by calculation of a hypothetical in situ burn of North Slope crude oil in the vicinity of Cook Inlet, Alaska. It is assumed that spilled crude oil is being burned in the confines of a fire resistant boom. Figure 1 presents the results from an example calculation for a steady burning fire for 1 hour with a burning area of 465 m^2 (5000 ft^2). In that figure, (A) is a typical atmospheric temperature profile for the Cook Inlet region in the winter. The effect of the temperature inversion on the plume rise is evident in (B) which shows the crosswind extent of hour-averaged plume particulate concentrations of 150 and 300 $\mu g/m^3$ at a cross section 5 km downwind of the burn site. (C) is a similar plot showing the downwind extent of these concentration levels in the plume. (D) displays the concentrations at the ground level, where the darker shaded areas indicate values higher than 150 $\mu g/m^3$. The term "ground level" refers to the first 10 to 20 m of the atmosphere, reflecting the resolution of the finite difference approximation of the conservation equations. In this example calculation, the concentrations of smoke particulate exceeding 150 $\mu g/m^3$ are confined to a small area less than 2 km long immediately downwind of the fire. Finally, (E) is included to quantify the previous contour plot. It shows the decrease in the ground concentration along the plume centerline. A comprehensive evaluation of many burn scenarios for the state of Alaska [7] showed that for a 465 m^2 burn, 150 $\mu g/m^3$ 1 hour average smoke particulate concentrations were not found at distances greater than 5 km downwind of the burn and did not extend beyond a width of 1 km. The 300 $\mu g/m^3$ 1 hour average ground level smoke concentrations were limited to less than 2 km downwind.

Finally, if doubling of the burning area to 930 m^2 (10,000 ft^2) is considered both the heat and mass release rates are assumed to be double, but the particulate concentrations near the ground are not double. The reason for this is that the plume will rise higher when the fire is larger in area. The higher elevation of the plume causes greater dispersion, and thus the particulate matter is spread over a larger area.

CONCLUSION

Smoke production from crude oil fires was found to vary with the area of the burn and the type of crude oil. It appears that 10 to 15 percent of the mass of crude oil burned in large areas is converted to particulate that is carried in the smoke plume. Calculations performed to predict near ground level concentrations of particulate from oil spill burns have shown

that 1 hour average concentrations do not exceed 150 $\mu g/m^3$ at downwind distances greater than 5 km and do not exceed 300 $\mu g/m^3$ beyond 2 km downwind of burns for a wide variety of weather conditions.

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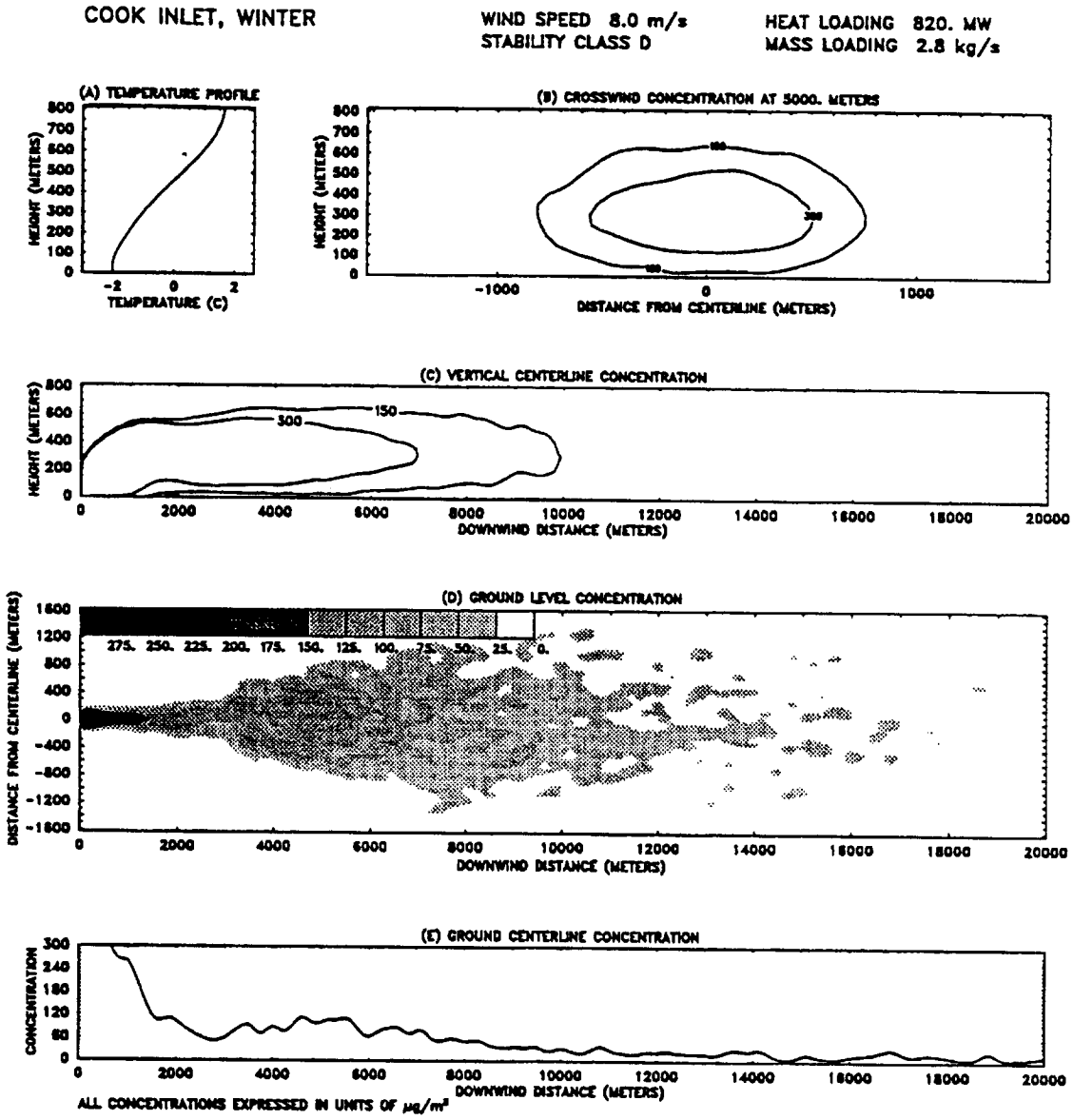

Figure 1. LES smoke plume calculations for in situ burning of a Alaska North Slope crude oil in the vicinity of Cook Inlet in the winter.